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RENOVATING THE EXISTING BUILDING STOCK: A LIFE CYCLE THINKING DESIGN APPROACH

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ABSTRACT

Considering Europe, the renovation of the existing building stock is getting more and more attention compared to the construction of new buildings. Indeed, a significant portion of the existing buildings has been built before the enforcement of modern standards concerning comfort, aesthetics, thermal efficiency and, especially for older buildings, seismic safety. In the case of renovation of existing buildings, it is important that the retrofit measures address most of the aforementioned issues in an integrated solution. Such measures should maximize resilience and safety and minimize the environmental impact of the intervention itself and of the operational use of buildings. A possible solution consists in carrying out the interventions mainly from the outside, minimizing the building downtime and the disturbance caused to users.

The Life Cycle approach and the Performance Based Design are fundamental methodologies for such integrated renovating projects. The combined use of both methodologies maximizes the structural and energy performance of the building, while minimizing, at the same time, the environmental impact of the intervention, the overall cost of the intervention and the operational costs.

The article addresses a feasibility study regarding the renovation strategies of a multi-story residential building, particularly focusing on the structural aspects. The paper also addresses the contribution in reducing the environmental footprint of the renovated building due to the reparability and sustainability of the intervention, and the disassembly, reuse or recycling of the components at the end of life. Finally, a comparison between a traditional design approach and the investigated integrated approach is presented.

Keywords: Life Cycle Thinking; Performance Based Design; Holistic renovation; Existing buildings.

1. INTRODUCTION

About 40% of existing European buildings was built more than 50 years ago, responding to the pressing housing problem following the Second World War (BPIE, 2011). At the time, in a lack of any seismic and energy regulations, buildings were rapidly erected with poor attention to the construction standards, the comfort of the inhabitants, and the social and urban environment. The resulting scenario is an obsolete building stock, with poor performances under an energy and structural point of view, with severe seismic vulnerabilities, and with poor formal and architectural features, leading to a low quality of life of the building users.

In order to increase the safety and wellbeing of the European citizens and to achieve the European standards in terms of energy consumption and greenhouse gas emissions, the **renovation of the existing building stock** is now a priority. The construction of few adequate new buildings is indeed not sufficient to improve the actual situation (Marini et al., 2014). In addition, due to the bad environmental conditions, the high structural decay, and the lack of economic resources, it is now

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recognized that the renovation of the existing buildings should adopt a **holistic approach**, as to improve all the structural, architectural, and energy deficiencies with a unique intervention (Marini et al. 2017). Such an approach would not only improve the condition of existing buildings and protect the human life, but would also further reduce the environmental impact of the constructions over their service life by reducing the probability of collapse in the case of natural disasters (Belleri and Marini, 2016).

Many researches have been recently focusing on new holistic solutions for the retrofit of existing buildings (Marini et al., 2017; Angi, 2016; Feroldi et al., 2013; Takeuchi et al., 2009), and many **integrated techniques** have been proposed. Some examples are: holistic exoskeleton for RC buildings (either adopting shear walls or shell/gridshell structure: Passoni et al., 2017; Labò et al., 2016); or steel (Misawa et al., 2015) and timber (Sustersic and Dujic, 2014; Della Mora et al., 2015) sandwich panels with both structural and energy functions. Many of the mentioned solutions are still at an initial stage of development and have not been yet tested to evaluate both the antiseismic and insulating performances.

While these new integrated techniques are under development, very few studies are now focusing on the tools needed to **design** holistic retrofit interventions. The design approach is still based on very sectorial codes and design regulations that lack of the global vision required by a holistic renovation process. The most updated state of the art regarding structural design – the performance-based earthquake engineering (PBEE) – is generally focusing on the sole traditional structural targets (total drift and base shear), with poor attention to some important structural responses of the retrofitted building (e.g. actions in the floor diaphragms or in the staircase walls). Moreover, it disregards the problems connected to the compatibility of the structural solutions with the energy and functional upgrade measures. Until now, the only attempt to include principles of sustainability are based on the inclusion of the life cycle assessment (LCA) of different proposed retrofit solutions (Loli et al., 2017), but considering the intervention “from cradle to gate”, and thus disregarding aspects connected to the sustainability of the intervention at the end of life and the impacts on the environment during the whole life-cycle (e.g. reparability after natural disaster or adaptability to possible building transformations).

This paper gives a first reinterpretation of the traditional performance-based design, proposing a **new multi-criteria performance-based design approach** accounting for criteria based on new structural targets, environmental sustainability, and social/economic sustainability of the retrofit intervention. These main topics are discussed, a framework for a new holistic design approach is outlined, and its feasibility is then verified by addressing such a framework for the renovation of a reference building typical of the post-WWII RC building stock.

2. A NEW MULTI-CRITERIA PERFORMANCE-BASED DESIGN INCLUDING LIFE CYCLE THINKING PRINCIPLES

A new approach to the design of retrofit interventions is here outlined, considering some issues connected to the structural and seismic renovation of an existing structure, the importance of including the principle of environmental sustainability and, in general, of Life Cycle Thinking in the design process, and the importance to study feasible interventions under an economic and social point of view. The new approach results in a revisited Performance-Based Design (PBD) for resilient, sustainable, and feasible interventions on the existing European building stock.

2.1 New criteria for the structural retrofit of existing buildings

The renovation of existing buildings requires additional design parameters with respect to new buildings. The sole control of the total drift or of the base shear is indeed insufficient to guarantee safety and to optimize the performances of the structure after the seismic upgrade. Some other important criteria should thus be considered, which are usually disregarded.

As a first point, the retrofitted building should form a **new seismic resistant system**. These systems are composed of floor diaphragms, vertical resistant elements, and foundations. When acting on existing buildings, the vertical resistant elements – either walls/bracings or shell/panels – are usually added or strengthened, but very often diaphragms and foundations are not addressed. Diaphragms are fundamental to transfer the floor inertia forces to the vertical elements; however, especially in the case of RC buildings, the capacity of the existing floors is frequently disregarded. Very few studies exist about the ability of the floors – especially one-way composite brick-RC ribbed floors – to act as diaphragms. Preliminary researches (Feroldi, 2014; Passoni, 2106) show that, even in absence of extrados concrete slab, this kind of floors is able to redistribute the seismic action by developing a resistant arch-and-tie mechanism in their depth. The maximum capacity of the floor depends on the resistance of the joist-block interface, the compression and tension strength of the clay blocks, and the tensile resistance of the RC edge beam acting as a tie (Marini et al., 2017). When the seismic action exceeds the floor capacity, the diaphragm should be retrofitted. Similarly, the capacity of the existing foundations should be checked for the additional forces induced by earthquakes and, when not verified, should be upgraded. The capacity of the existing floors and foundations represent thus additional targets that should be controlled in the design of the seismic retrofit interventions.

Another important criterion that should be observed in a performance-based design of a structural retrofit intervention is the **protection of the escape path**; however, the actions in the staircase walls are usually never controlled, especially if they are masonry infill walls. An ongoing research is assessing the role of the staircase wells in the seismic response of RC buildings (Cavalli et al., 2016). In general, the staircase wells should always be verified to the seismic loads and protected through the retrofit intervention.

Finally, a Performance-Based Design (PBD) should also be able to **reduce the damage after natural disasters** to both structural and nonstructural elements as to facilitate the rescue operations in the post-earthquake emergency, reduce the reconstruction costs, and reduce the waste. It has been observed that about 50-70% of the total direct losses due to earthquakes is connected to non-structural elements (Whittaker and Soong 2003). A fair calibration of the structural design targets may thus foster a better sustainability of the intervention and protection of the investment. For example, in the case of reinforced concrete structures, it is possible to reduce the targets in terms of interstorey drift as to limit damage to the infills. Otherwise, some low-cost preliminary interventions may be carried out in order to reduce the stiffness of the building and, consequently, the entity of the retrofit intervention (Passoni, 2016; Preti et al., 2015; Fardis and Panagiotakos, 1997; INSYSME, 2016).

2.2 New criteria fostering environmental sustainability: LCT approach

In the last few years, European Roadmaps (2020 and 2050) envisioned the transition toward a low-carbon eco-efficient society. This led to the promulgation of new requirements in terms of emissions and energy consumption for new buildings. However, considering the current state of preservation of the existing building stock, the EU targets may only be reached by acting on the existing buildings and by adopting **smart and sustainable interventions**.

Learning from the past, which led to such an impacting building stock, new concepts may be proposed for the design of retrofit techniques. These concepts consist in minimizing the impacts over the whole life cycle of the building by accurate selection of technologies, materials, and components, through a Life Cycle Thinking approach.

The **Life Cycle Thinking** (LCT) is an approach to the design of a product that is not just limited to the control of its performances, but it also includes the study of its impacts throughout its life (ISO 14040, 2006). In the case of building renovation, these principles may lead to holistic interventions that are fully demountable and recyclable, adopt sustainable materials (Thormark, 2006), and are easily repairable after an extreme event. Solutions should lump the damage into structural fuses as to protect the main structural components and the energy and architectural layers. To ensure easy assemblage and demountability of the components, pre-fabrication and dry techniques should be adopted. This makes the system adaptable to possible innovative technologies and to possible new functions of the structures. Finally, the end-of-life scenario of the retrofitted building should be addressed, and demountability, reusability and recyclability of the additional components should be guaranteed in order to reduce the amount of waste (Marini et al., 2017).

All these principles can be considered as additional criteria for the new multi-criteria PBD in order to foster the environmental sustainability of the renovation process. Together with the LCT, the new PBD allows to control additional parameters in order to minimize the environmental impact of the intervention and of the retrofitted building, the overall cost of the intervention and the operating costs in terms of CO_2 during the whole life cycle. These criteria make it possible to compare different solutions with same structural and energy performances with a LCT approach.

2.3 New criteria fostering social-economic sustainability

Many techniques have been studied to improve the energy and/or structural performances of an existing building; however, the feasibility of the retrofit interventions is not always considered. Frequently, seismic interventions – especially when "local" – are very expensive since they entail the demolition of the building finishes and often require the relocation of the inhabitants and of other building activities. The direct and indirect costs of those interventions are thus so high that they are rarely applied.

In order to foster the social-economic sustainability of the seismic retrofit interventions, two main criteria should be pursuit: adopting holistic solutions, which couple the structural renovation with the energy and architectural upgrade, and avoiding the relocation of inhabitants by applying the intervention from outside the building.

As for the **holistic interventions**, some economic co-benefits may be attained with the holistic approach besides the reduction of the environmental impact, the elongation of the structural service life, and the improvement of the resilience (Marini et al., 2017): a) the costs of the structural intervention may be partially covered by the savings obtained with the energy upgrade; b) costs and duration of the intervention may be reduced due to the shared construction site; c) a long-term protection of the investment may be guaranteed, otherwise jeopardized by the damage due to either earthquakes or structural decay; d) new living spaces may be added (e.g. new balconies and loggias or even new stories) thus increasing the commercial value of the building.

The relocation of the inhabitants is one of the major barriers to the renovation of the existing buildings. The study of structural retrofit intervention exclusively applied **from outside** should thus be endorsed. The design of those solutions implies the definition of additional structural requirements. For example, additional diaphragms cannot be realized at the extrados of the floors, but they should be put at the intrados, or a gallery should be added outside the building and its floor could be conceived as an external floor diaphragm. Moreover, new foundations may be required for the additional exterior elements, but this may avoid the retrofit of the existing foundation system, which is usually an expensive and time-consuming operation.

2.4 Proposal of a new multi-criteria PBD targeting safety, resilience, and sustainability

All these new criteria transform the traditional PBD approach into a new multi-criteria approach, which also includes the principles of Life Cycle Thinking to account for environmental and social-economic sustainability. Besides considering new structural targets to control the seismic response of retrofitted existing buildings, to protect the escape route, and to reduce the damage to structural and nonstructural elements, the principles of LCT are considered to compare different holistic interventions with similar energy and structural performances (Figure 1). The comparison should be based on quantitative or qualitative criteria and would enable selecting the optimal solution.

The new criteria include, for example (Passoni, 2106):

- *for the construction and use phase of the building*: cost of the solution, construction time, need to relocate the inhabitants, need for maintenance;
- *for the post-earthquake phase*: costs for the repair of the intervention and of the building, need of relocation of the building functions, other impacts associated with the repair (amount of waste, raw materials and energy consumption, etc. .);
- *for the end-of-life phase*: impacts associated with the demolition of the building, possibility of down-cycling, re-cycling or re-use, up-cycling of the structural elements, LCA (Life Cycle Assessment), LCC (Life Cycle Costs).

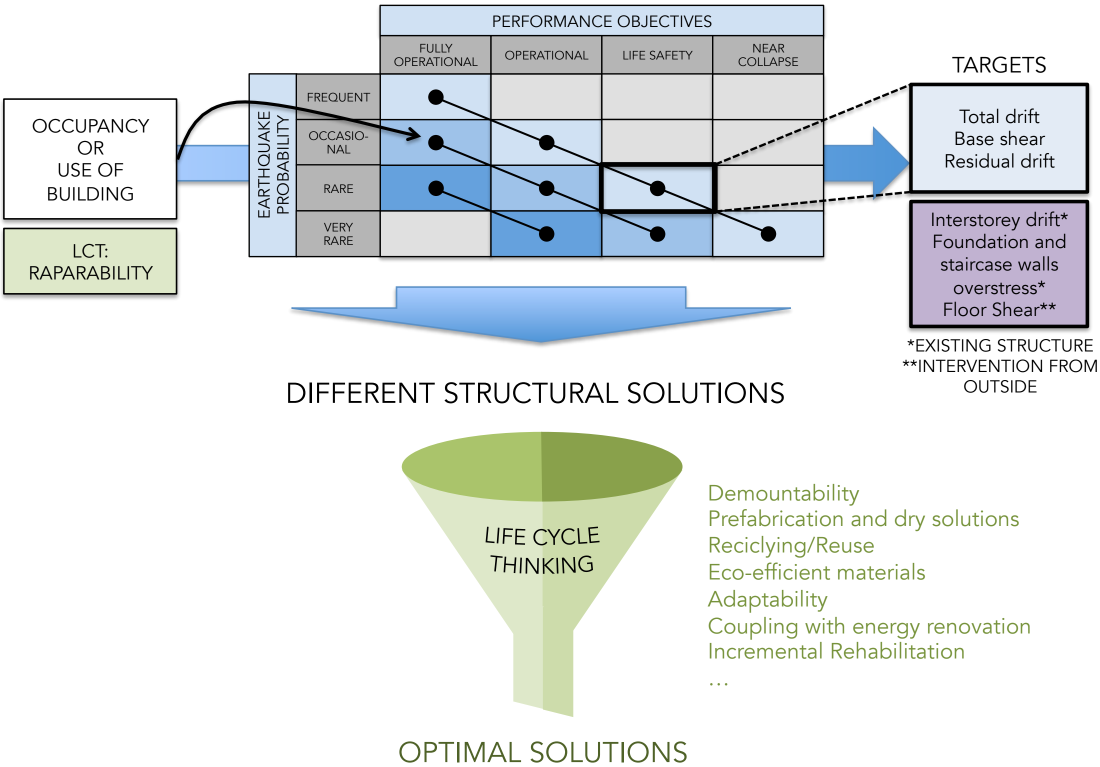

Figure 1. Conceptual scheme of the new multi-criteria performance-based design approach.

3. APPLICATION TO A REFERENCE BUILDING

The feasibility of the proposed multi-criteria Performance Based Design method is here validated for the design of a holistic intervention on a RC building typical of the European post-WWII building stock. The drawbacks connected to a traditional design approach are outlined and the LCT approach is then applied.

The structure is first described and analyzed in the as-is situation. The importance of assessing the role of the staircase walls in the evaluation of the seismic response of the building is highlighted. The seismic retrofit of the building is then designed considering both a traditional approach and the proposed multi-criteria PBD approach. Two different solutions are finally designed: the addition of exterior RC walls, which is a typical solution for the retrofit of existing post-WWII RC buildings, and the addition of exterior steel bracings with the same structural performances in terms of stiffness and resistance. The multi-criteria PBD is then applied to compare those different solutions considering LCT-based criteria. The best retrofit option is finally selected.

3.1 Reference building

The reference building considered for the application of the integrated intervention is an Italian residential multi-storey building built in 1973. The structure consists of an infilled RC frame with eight floors above ground (H= 24.75m) and with a slightly irregular plan with gross dimensions 27.5m x 13.5m (Figure 2).

As it is typical for this kind of buildings, the structure consists of three one-way frames arranged longitudinally and composed of nine columns. The Northern frame is interrupted by the presence of the stairwell and the elevator shaft, which were originally designed to withstand the sole vertical loads. The floors are one-way composite brick-RC floors, which are able to resist in their plane thanks to an arch-and-tie mechanism (Feroldi, 2014; Passoni, 2106).

The building has direct foundations, and it has been considered as fixed at the base.

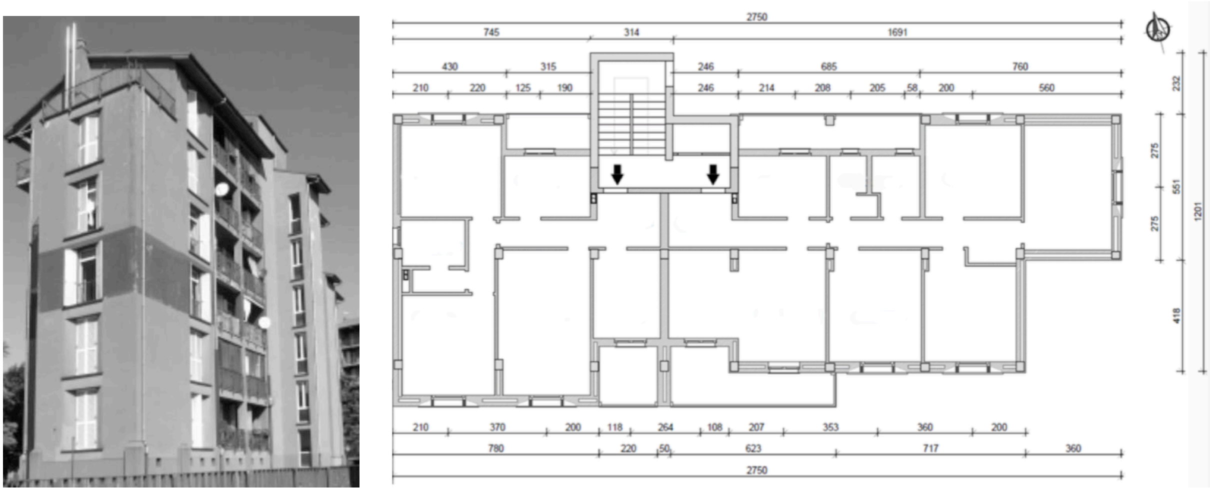

Figure 2. Reference RC building typical of the European post-WWII building stock: external view and plan

3.2 Seismic vulnerability analysis

The building has been modeled with the commercial software MIDASGen (2018). The characteristics of the structure have been obtained from the original construction documents and the properties of the materials from in situ tests. In the analysis C25/30 grade for the concrete and FeB44k grade for steel were considered.

In the model, beams and columns have been modeled as beam elements with lumped plasticity and the shear and flexural hinges have been calculated in accordance with the Italian building code (NTC, 2008). For the sake of simplicity, the beam and column sections have been standardized. In particular, 30cm x 60cm columns with 6ϕ16 have been considered at the ground floor and 30cm x 50cm columns with 6ϕ14 have been adopted on the remaining floors; as for the beams, a section of 30cm x 42cm with 2ϕ14 at the top and 4ϕ14 at the bottom was considered.

A sensitivity analysis showed that this simplification did not significantly alter the building's response to horizontal loads, compared to a significant reduction in computational costs.

The infill walls, made of clay hollow blocks, have been modeled as compression only struts converging in the nodes. The dimensions of the struts have been calculated in accordance with Decanini et al. (1993) resulting in a thickness t=300mm and a width w=978mm; as for the force-displacement behavior, the curve shown in Figure 3 has been considered. This kind of infills has also been considered in the stairwell in order to evaluate the influence of these elements on the overall response of the building.

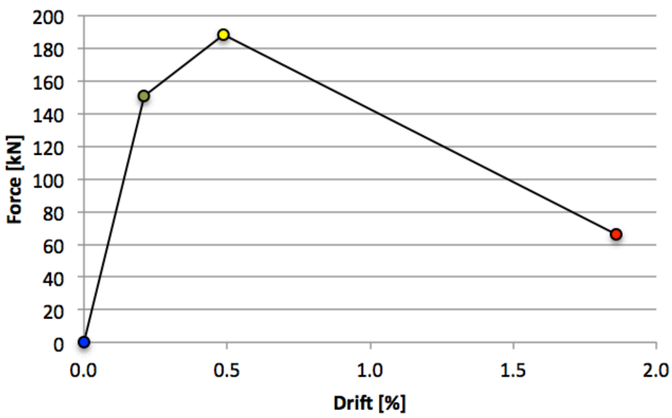

Figure 3. Force-drift relationship for the masonry infills (blue: elastic branch, green: yielding resistance, yellow: peak resistance, red: residual resistance).

The response of the building to seismic loads has been evaluated by means of static non-linear

analyses.
The response curve of the building in the as-is situation, obtained with pushover analyses, is shown in Figure 4, where the displacement demand at the Life Safety Limit State (LSLS; return period of 475 years) is calculated considering the building located in L'Aquila and a ground category C according to the Italian code (NTC, 2008). The sole transverse direction has been considered, being the most unfavorable; however, similar considerations have been obtained for the longitudinal direction.

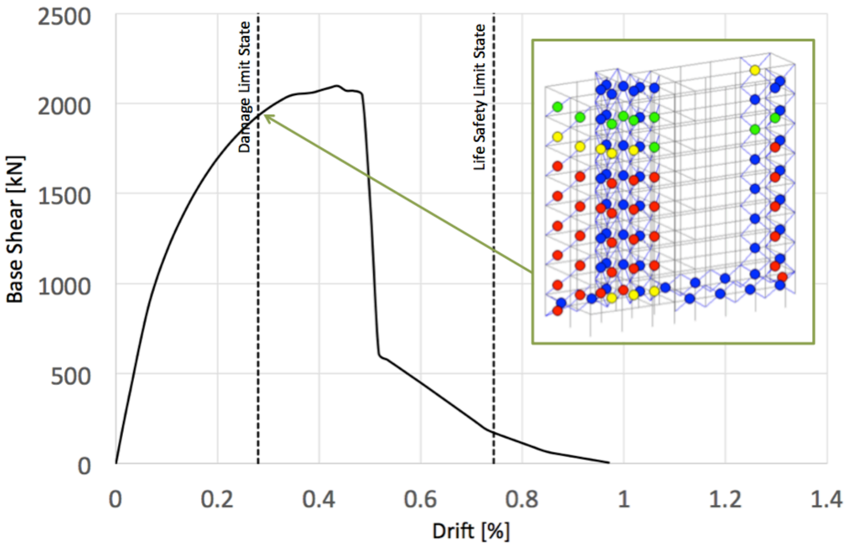

Figure 4. Capacity of the building in the as-is situation compared to the displacement demand at the Damage and Life Safety Limit State considering the building located at L'Aquila (Italy) (according to the Italian building code, NTC 2008); in the box it is shown the state of the masonry infills and staircase walls at the Damage Limit State (blue: elastic, green: yielding resistance, yellow: peak resistance, red: residual resistance)

From the analysis of the curve, it may be observed that the building shows bad performances for seismic loads. The structure collapses due to the activation of a weak floor mechanism at the ground level in correspondence of a 0.50% drift. In addition, for a drift equal to 0.28% there is the collapse of both the external infills and the stairwell. An earthquake with return period of 50 years (Serviceability Limit State according to the Italian building code, NTC 2008) may therefore lead to failure of the stairwell, thus compromising the only escape route.
In addition, the drift capacity of the building is way lower than the drift demand at the Life Safety Limit State of the reference earthquake (L'Aquila, LSLS). The building is thus not verified according to the Italian building code (NTC 2008) and would need structural interventions in order to resist to the design seismic loads.
Although the influence of the infills on the seismic behavior of buildings has been widely discussed in the literature (Dolšek and Fajfar, 2008; Manfredi et al., 2012), very few has been studied about the problem of the stairwell, which instead has a major role on the building's response and has a clear impact on the safety of the inhabitants (Cavalli et al., 2017).

3.3 Design of the intervention: influence of additional structural criteria

Being the building in the as-is situation unable to withstand the design seismic loads, a seismic retrofit intervention has been designed. In order to guarantee the feasibility of the intervention, a retrofit solution that may be applied exclusively from outside and may be coupled with energy and architectural renovation of the building has been considered.
Two different approaches were considered for the design: a traditional approach and the multi-criteria design approach, which also takes into account the presence of the staircase walls and of the existing floors after the retrofit intervention.
In the traditional approach, a displacement target lower than the LSLS displacement demand should be imposed, and the response of the retrofitted building should be assessed by means of nonlinear static

analyses. Considering the transversal direction, the reference building is verified to the LSLS by adding to the existing structure two walls with total stiffness ($K_{retrofit}$) equal to 2.5 times the stiffness of the existing building ($2.5K_{frame}$). From Figure 5, it may be observed that this retrofit intervention leads to an improvement of the building performances both in terms of resistance and ductility. However, by observing the distribution of the damage in the structure at the design earthquake (L'Aquila, LSLS), the ultimate capacity is reached in the infill walls, staircase walls, and in the existing floors. This would require both the upgrade of existing floors to behave like rigid floor diaphragms and the retrofit of infills walls, especially in the stairwell in order to protect the escape route.
When applying the proposed multi-criteria PBD for the assessment of the behavior of the retrofitted building, the initial targets should thus be corrected to satisfy those additional structural criteria. For the reference building, the stiffness of the intervention was therefore increased to 3.5 times the stiffness of the existing building ($3.5K_{frame}$) in order to limit the interstorey drift of the retrofitted building and consequently have the protection of both the human life and the investment. This new retrofit intervention further improves the building's performances, leading to a stiffer building that has also higher ductility and higher resistant capacity (Figure 5). Moreover, infills and stairwell do not experience any damage for the design earthquake.
As for the floor diaphragms, their overload is avoided by adopting an accurate choice of the additional wall distribution. Considering an arch-and-tie resistant mechanism, the number of arches and their span are determined by the distance between adjacent walls. A proper distribution of the walls has thus been calculated in order to reduce the stress in the existing floors, exploiting their maximum design capacity equal to τ_d = 1MPa at the interface between joists and blocks (the weakest point of the system) (Feroldi, 2014; Passoni, 2016). The resulting configuration is reported in Figure 6.

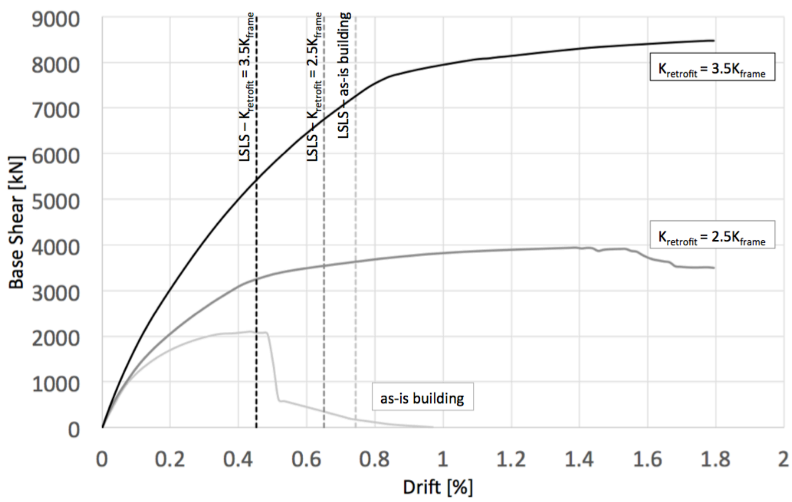

Figure 5. Capacity of the building in the as-is situation (light grey), of the building retrofitted with an intervention with $K_{retrofit}$=$2.5K_{frame}$, and of the building retrofitted with an intervention with $K_{retrofit}$=$3.5K_{frame}$ compared to their displacement demand at the Life Safety Limit State considering the building located at L'Aquila (Italy) (according to the Italian building code, NTC 2008)

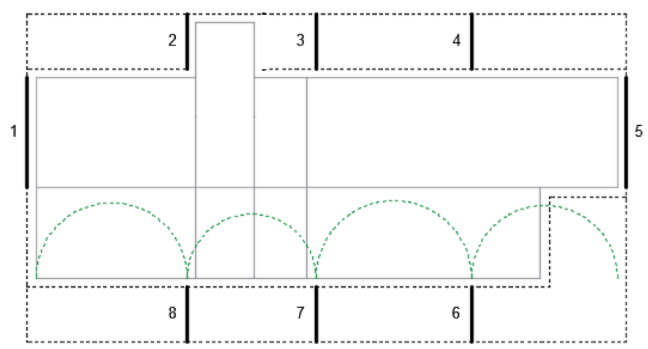

Figure 6. Distribution of the additional walls to reduce the diaphragm's overload (in the RC wall solution the walls 1 and 5 on the façade are split in two walls).

Based on the obtained design stiffness ($3.5K_{frame}$), two different retrofit techniques have been considered: additional RC walls and additional steel bracings, both arranged as in Figure 6.
The RC wall solution consists of ten walls with dimensions 270cm x 30cm (four located along the façade and six in the transversal direction), considering a C30/37 concrete with an elastic modulus reduced by 50% to consider concrete cracking.
On the other hand, the steel bracing solution consists in concentric diagonal bracing made of S355 steel and variable sections. On the façade there are two bracing of 5.13m, with beams and columns consisting of circular profiles with 244.5mm diameter and 16mm thickness and diagonals with 139.7mm diameter and 6mm thickness; while along the two longitudinal sides there are six bracings, with a plan dimension of 2.55m, beams and columns equal to the front, and diagonal elements with 101.6mm diameter and 10mm thickness.
For both solutions foundation piles are required to withstand the design seismic loads of the new shear walls.

3.4 Selection of the best retrofit option according to the LCT principles

At the end of the design process, the two proposed solutions have been finally compared by addressing the proposed multi-criteria PBD, thereby considering criteria of sustainability in accordance to a Life Cycle Thinking approach. Considering that the solutions feature the same structural performances, aspects related to the environmental, social and economic impact were analyzed to assess the sustainability and feasibility of the interventions.
A qualitative comparison was carried out for some criteria at the construction and use phase of the building, at the post-earthquake phase and at the end of life of the building. The analysis is shown in Table 1.

Table 1. Comparison of the designed solutions adopting a Life Cycle Thinking approach.

	RC walls	**Steel walls**
	Construction and Use Phase	
Construction time	medium	low (prefabricated solution)
Construction costs	medium-low	medium-high
Need of inhabitants' relocation	no (from outside)	no (from outside)
Fast assembling and disassembling	no	yes
Adaptability to building functions during its life cycle	no	yes
Need of maintenance	low	low
	Post earthquake phase	
Repair costs	high (demolition may be required)	low (damage is lumped in the diagonals or in sacrificial elements)
Impacts connected to the repair operations	high (demolition may be required)	low (damage is lumped in the diagonals or in sacrificial elements)
Building downtime	low (from outside)	low (from outside)
	End-of-Life	
Recyclability	no	yes
Reusability	no	yes

As a result of this first qualitative comparison, the solution with steel bracings, although having the same structural performance of the solution with RC walls, is shown to be preferable with respect to all those parameters connected with the principles of sustainability and LCT.

4. CONCLUDING REMARKS

The transition toward a low-emission, safe, and resilient society needs the renovation of the existing building stock under a structural, seismic, energy, and architectural point of view. Although many technologies have been studied in recent years, little has been done to adapt the current sectorial approach for the design of retrofit interventions to this new holistic vision.

In this paper, a first attempt to upgrade the current design approach has been made by proposing a new multi-criteria Performance Based Design including the principles of Life Cycle Thinking. The combined use of both methodologies maximizes the structural and energy performance of the building, while minimizing, at the same time, the environmental impact of the intervention, the overall cost of the intervention and the operational costs. This new approach has been applied, with reference to the structural aspects, in the hypothesis of a holistic renovation of a RC multi-storey residential building typical of the European post-WWII heritage. For the reference building, focus was made on:

- the importance of considering the contribution of stairwells – rather than just infill walls – in the study of the seismic behavior of the existing structures. These elements are usually very stiff and were not designed to withstand horizontal loads. This aspect is rarely considered, but it is quite relevant since the stairwells are often the only escape routes for the inhabitants. The overstress of the existing floors and foundations in the post-intervention conditions were also addressed;
- the application of a new multi-criteria performance-based design, which considers additional structural parameters to control the performance of existing buildings. In addition to targets like total drift and base shear, other parameters such as interstorey drift, stairwell overload and floor overload were considered. For the reference building, such additional targets lead to an increase of the stiffness of the intervention since a drift smaller than the maximum displacement demand at the design earthquake was required. A higher displacement of the building would have jeopardized the escape route of the building and would have entailed expensive repairs to the non-structural elements following the earthquake, thus not ensuring investment protection. As an alternative to the stiffness increase, which may lead to higher dimensions and costs of the retrofit intervention, downgrade solutions (Ireland et al., 2006) or preliminary upgrade of the non-structural elements could have been applied;
- finally, it was shown how the principles of LCT and PBD can be coupled to perform comparative analyses between solutions with the same structural performances. For the reference building, just qualitative comparisons were carried out, but an ongoing research is aimed at defining a Multi Criteria Decision Making tool for the definition of the best retrofit options (Caterino et al., 2009).

5. ACKNOWLEDGMENTS

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